Late Pleistocene cold-climate loess deposits of Beringia

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The geological record from Arctic and Subarctic regions indicates that aeolian activity was much more extensive during Pleistocene cold stages than in warm stages, leading to widespread deflation, erosion and deposition of silt and sand (Hopkins, 1982; Astakhov, 2014). The heartland of the windy periglacial world was in the plains of Beringia, where silty deposits now frozen in permafrost underlie hundreds of thousands of square kilometres of lowlands in central and northern Siberia, significant areas of central and northern Alaska and the Klondike region of Yukon, Canada.

The silt forms a distinctive stratigraphic unit 3–80 m thick that is rich in ground ice and organic carbon, and blankets many Beringian lowlands and foothills. Such *yedoma* preserves an exceptional terrestrial sedimentary record of Late Pleistocene environmental history (Schirrmeister *et al*., 2013). Cold permafrost conditions during yedoma accumulation limited oxidation of organic material, preserving remains of the former steppe-tundra ecosystem, including plant roots, mammal bones and carcasses, pollen, insect remains, plant macrofossils, fossil rodent burrows, soil DNA and microbial communities immobilised on the surface of ancient seeds. Much of the organic material is vulnerable to decomposition and production of greenhouse gasses CO_2 or CH_4, if the yedoma thaws. The organic material within yedoma accumulated through incremental sedimentation and continuous upward growth of permafrost over thousands of years. However, different geological interpretations of yedoma persist between researchers in eastern Beringia (Alaska and Yukon) and western Beringia (northeast Siberia) (Brigham-Grette, 2001). The differences are fundamental to understanding the geology and palaeoecology of Beringia, the sedimentary processes that led to sequestration of hundreds of Pg of carbon (Kuhry *et al.,* 2013) and whether yedoma provides a globally significant record of ice-age atmospheric conditions or just regional floodplain activity.

A new multidisciplinary and international study of yedoma at the Russian type site of Duvanny Yar, in the Lower Kolyma valley of northeastern Yakutia, has interpreted most of the silt there as a cold-climate loess-palaeosol sequence (Figure 1; Murton *et al.,* 2015). The study has resolved the problems associated with the alluvial-lacustrine and polygenetic hypotheses favoured by Russian permafrost scientists, and explained: (1) the absence of primary sedimentary stratification in most of the yedoma silt in terms of airfall (primary) loess; (2) the occasional faintly stratified layers of yedoma silt in terms of reworked (secondary) loess; (3) the bi- to polymodal particle-size distributions in terms of mixing of populations of grains derived from different sources and transported by different wind-driven mechanisms; and (4) the sequence of buried palaeosols in terms of a loess-palaeosol sequence. Although the bulk of the yedoma silt at Duvanny Yar is interpreted as primary (airfall) loess that settled from suspension, occasional indistinctly stratified silt may have been redeposited on low-angle slopes, particularly in view of annual snowmelt operating on an undulating palaeo-land surface.

The Duvanny Yar loess is consistent with evidence of widespread aeolian activity in the Late Pleistocene of Beringia and Eurasia. In northwestern North America, dunefields, sand sheets, sand wedges and composite wedges, deflation areas and loess characterised much of the unglaciated region, particularly during Marine Isotope Stage (MIS) 2, and extended into deglaciated regions (Figure 2). On the north Alaskan Arctic Coastal Plain a Late Pleistocene sand sea (*Ikpikpuk Dunes*) grades distally into the loess belt along the foothills of the Brooks Range and proximally into a region with large aeolian sand wedges. Farther east, on the Canadian Arctic Coastal Plain another Late Pleistocene sand sea (*Kittigazuit Dunes*) developed on the Tuktoyaktuk Coastlands and offshore across the emergent eastern Beaufort Sea Shelf, NWT. Large sand wedges and composite wedges of Late Pleistocene age developed widely in this region, particularly during deglaciation of the Laurentide Ice Sheet. In central and northern Asia, deflation deserts covered large regions from

Mongolia to the Laptev Sea and were associated with intensive release of sand and silt, and subsequent deposition as aeolian sand and thick accumulations of loess (yedoma). Loess deposited in the Yakutsk region of central Yakutia and the Kolyma-Indigirka-Yana lowlands of northern Yakutia today remains deeply frozen in permafrost, whereas loess that originally accumulated under permafrost conditions in southern Siberia is now unfrozen (Figure 3).

The Duvanny Yar loess represents part of an extensive cold-climate loess deposit that stretches westwards from northeast Yakutia through central Yakutia to the loess belt of Europe and eastwards to the loess of eastern Beringia. The loess represents a gradation between two end members. One constitutes very ice-rich loess (yedoma) characteristic of continuous permafrost that existed throughout MIS 4 to 2 in much of Beringia and central Yakutia and persists to the present day within continuous to discontinuous permafrost. The other constitutes ice-poor loess characteristic of permafrost that developed episodically in northwest Europe and in western and central Siberia, where permafrost degraded during the last glacial-interglacial transition. Persistence of cold continuous permafrost conditions during loess deposition at Duvanny Yar led to stacking of ice-rich transition zones and growth of large syngenetic ice wedges characteristic of yedoma. By contrast, episodic permafrost conditions in warmer regions to the south and west led to repeated permafrost thaw and development of small ice wedges represented by ice-wedge and composite-wedge pseudomorphs in southern Siberia and northwest Europe.

Now that the yedoma of western Beringia is interpreted primarily as loess rather than floodplain deposits, the next stage of research is to reconstruct a record of ice-age atmospheric conditions (e.g. dust inputs, wind intensity) in northeast Eurasia and compare it with the patterns and timings of environmental changes inferred from ice-core, ocean sediment and lake sediment sequences elsewhere. This requires high-resolution sampling and analysis of permafrost drill cores through Siberian yedoma.

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Figure Captions

Figure 1 Yedoma silt (dark grey) criss-crossed by syngenetic ice wedges (light grey) in headwall of a thaw slump at Duvanny Yar. Melting of polygonal ice wedges has left conical thermokarst mounds of yedoma (baydzherakhs) upstanding on the headwall. Larch trees tilted and fallen on headwall as a result of permafrost thaw and ground surface slumping. Scale given by people in left centre of photograph.

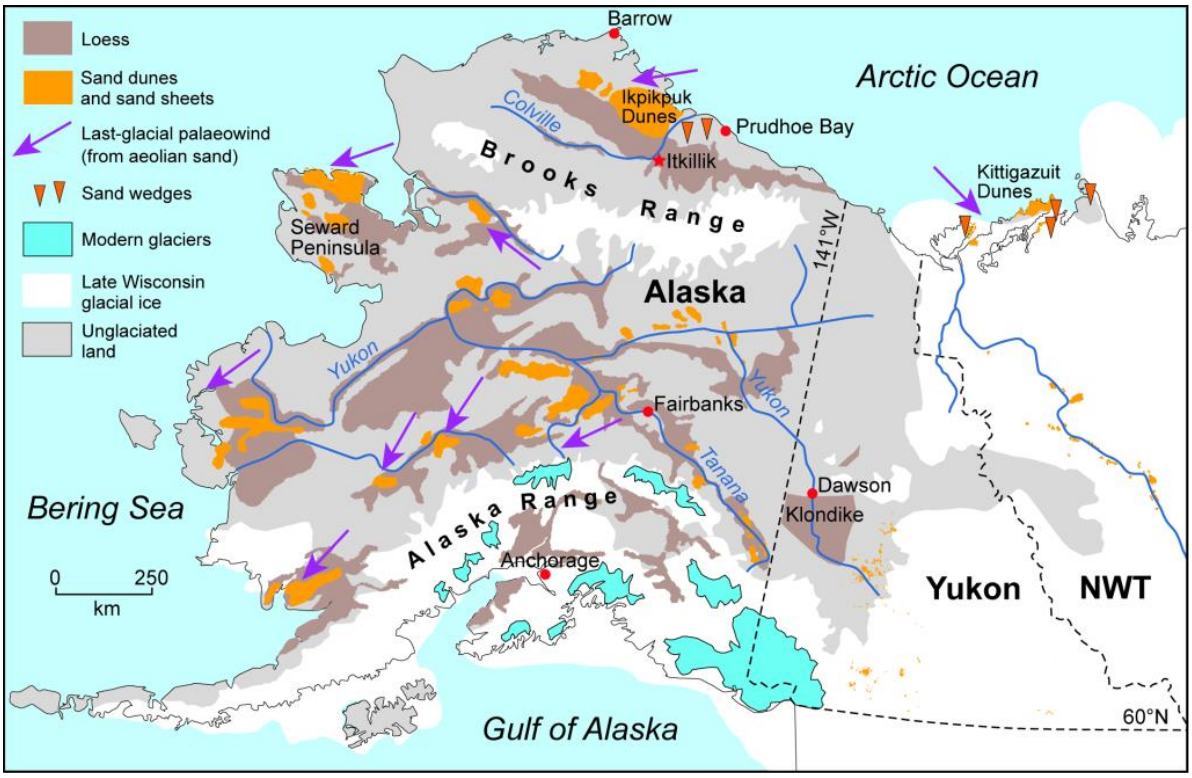

Figure 2 Distribution of aeolian deposits of northwestern North America. Sources listed in Murton et al. (2015). (Reproduced from Murton, J. B. *et al.* (2015). Palaeoenvironmental interpretation of yedoma silt (Ice Complex) deposition as cold-climate loess, Duvanny Yar, northeast Siberia. *Permafrost and Periglacial Processes,* vol. 26, pp. 208–288, with permission from John Wiley and Sons, where sources are listed).

Figure 3 Distribution of aeolian deposits and deserts during the last glacial (MIS 2) in central and northern Asia. BL = Bol'shoy Lyakhovsky. (Reproduced from Murton, J. B. *et al.* (2015). Palaeoenvironmental interpretation of yedoma silt (Ice Complex) deposition as cold-climate loess, Duvanny Yar, northeast Siberia. *Permafrost and Periglacial Processes,* vol. 26, pp. 208–288, with permission from John Wiley and Sons, where sources are listed).